NPS-57P176031

NAVAL POSTGRADUATE SCHOOL
Monterey, California

The Oscillating Jet Flap

Max F. Platzer

March 1976

Approved for public release; distribution unlimited

NAVAL POSTGRADUATE SCHOOL

Monterey, California

Rear Admiral I. W. Linder	Jack R. Borsting
Superintendent	Provost

This report was prepared by:

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
NPS-57P176031

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
The Oscillating Jet Flap

5. TYPE OF REPORT & PERIOD COVERED

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
MAX F. PLATZER

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Postgraduate School
Monterey, California 93940

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS

12. REPORT DATE
March 5, 1976

13. NUMBER OF PAGES

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)

15. SECURITY CLASS. (of this report)

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Unsteady Aerodynamics
Jet Flap
V/STOL Aerodynamics

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This document is the written version of a lecture presented in the Short Course on High Lift Technology at the University of Tennessee Space Institute, October 27-31, 1975.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Table of Contents

I. Introduction

The steady aerodynamic characteristics of the jet flap and its derivatives have been studied rather extensively over the past two decades and a considerable body of information including a general computer program (Ref. 12) for its prediction is now available. The unsteady jet flap characteristics are much less understood although the potential of the jet flap as a fast acting lift control device was recognized quite early. In the last few years there was a noticeable increase in activity on this problem ranging from experimental/theoretical studies of the jet flap's frequency response to applications for wind tunnel dynamic response investigations as well as aircraft and helicopter gust load and vibration control. It is the objective of this lecture to present an up-to-date review of these activities.

2. Unsteady Jet Flap Theory

2.1 Basic Theory

Assume an airfoil that has a jet emerging at the trailing-edge. Both the airfoil and jet are free to execute a small amplitude but otherwise arbitrary time-dependent motion. The jet is assumed to extend infinitely far downstream and both the main-stream flow and the flow in the jet are taken to be inviscid, incompressible and irrotational. Furthermore, it is assumed that the local jet velocity v is very much greater than the local velocity of the main stream u in the vicinity of the jet. The total pressure in the jet is, for $v >> u$, greater than that in the main stream which requires in the absence of viscous mixing and because of the continuity of static pressure across the jet boundaries that a vortex sheet satisfies the velocity discontinuity there.

In the main stream the unsteady Bernoulli equation must hold

$$p + \frac{\rho_o u^2}{2} + \rho_o \frac{\partial \phi}{\partial t} = p_o + \frac{\rho_o U_o^2}{2} \tag{1}$$

where p, ϕ, u are the local static pressure, velocity potential and velocity, respectively. ρ_o is the constant density, the subscript zero denotes conditions at infinity. Similarly, in the jet one has

$$p + \frac{\rho_J v^2}{2} + \rho_J \frac{\partial \phi_J}{\partial t} = p_o + \frac{\rho_J V_o^2}{2} \tag{2}$$

where p, ϕ_J, v are the local static pressure, velocity potential and velocity in the jet, ρ_J is the constant but in general different jet density, p_o and V_o are the static pressure and velocity at infinity downstream independent of time. This is based on the assumption that sufficiently far downstream at a given instant of time after initiation of the motion, the jet must return to

its initial undisturbed position, requiring also that its slope and curvature vanish. Therefore, one has the condition

$$\lim_{\substack{x \to \infty \\ t \text{ fixed}}} Y(x,t) = \lim_{\substack{x \to \infty \\ t \text{ fixed}}} \frac{\partial Y(x,t)}{\partial x} = \lim_{\substack{x \to \infty \\ t \text{ fixed}}} \frac{\partial^2 Y(x,t)}{\partial x^2} = 0 \qquad (3)$$

The following argument is advanced to justify this statement (Erickson 1962): Since the jet is impermeable and extends to infinity downstream a particle above (or below) the jet initially must always remain above (or below). If the jet were displaced from its initial position at infinity downstream, an infinite amount of work would have been done in a finite time to move the infinite amount of air above and below the jet.

Also, since the flow in the jet is irrotational one has

$$\frac{\partial v}{\partial r} + \frac{v}{r} = 0$$

where r is the radius of curvature of the streamlines. Integration of this equation then gives

$$rv = \text{Constant} \qquad (4)$$

To obtain the pressure difference across the jet consider an incremental jet element shown in Fig. 1. Subscripts 1 and 2 refer to upper and lower jet boundaries. $R(s,t)$ is the radius of curvature, $\delta(s,t)$ the jet thickness at position s and time t.

From Eq. (2) one obtains

$$p_1(s,t) - p_2(s,t) = -\rho_J \frac{v_1^2(s,t) - v_2^2(s,t)}{2} - \rho_J \left\{ \frac{\partial \phi_{J_1}(s,t)}{\partial t} - \frac{\partial \phi_{J_2}(s,t)}{\partial t} \right\}$$

$$= -\rho_J \frac{v_1(s,t) + v_2(s,t)}{2} \left[v_1(s,t) - v_2(s,t) \right] - \rho_J \frac{\partial}{\partial t} \left[\phi_{J_1}(s,t) - \phi_{J_2}(s,t) \right]$$

However, since the radii of curvature are normal to the streamlines inside the jet they are equipotentials of the jet flow. Hence

$$\phi_{J_1}(s,t) - \phi_{J_2}(s,t) = 0$$

Defining the mean jet velocity as

$$V(s,t) = \frac{v_1(s,t) + v_2(s,t)}{2}$$

the irrotationality condition Eq. (4) becomes

$$v_1(s,t) \left[R(s,t) - \frac{\delta(s,t)}{2} \right] = v_2(s,t) \left[R(s,t) + \frac{\delta(s,t)}{2} \right]$$

and therefore

$$v_1(s,t) - v_2(s,t) = \frac{V(s,t)\ \delta(s,t)}{R(s,t)}$$

Substituting the above equations back into the equation for the pressure difference across the jet one finally obtains

$$p_1(s,t) - p_2(s,t) = -\frac{\rho_J V^2(s,t)\ \delta(s,t)}{R(s,t)}$$

$$= -\frac{J(s,t)}{R(s,t)} \qquad (5)$$

where the jet momentum is

$$J(s,t) = \rho_J V^2(s,t)\ \delta(s,t) \tag{6}$$

Eq. (5) shows that the pressure difference across the jet is proportional to the jet momentum flux and inversely proportional to the radius of curvature of the jet. This is analogous to the steady jet flap result and was achieved by the assumption $v >> u$ causing the vanishing of the velocity potential difference across the jet.

Having expressed the pressure difference across the jet it is next required to determine the jet vortex strength. Using Eq. (1) for the main stream across the jet one obtains

$$p_1(s,t) - p_2(s,t) = -\rho_o \frac{u_1^2(s,t) - u_2^2(s,t)}{2} - \rho_o \left\{ \frac{\partial \phi_1(s,t)}{\partial t} - \frac{\partial \phi_2(s,t)}{\partial t} \right\}$$

$$= -\rho_o \frac{u_1(s,t) + u_2(s,t)}{2} \left[u_1(s,t) - u_2(s,t) \right]$$

$$- \rho_o \frac{\partial}{\partial t} \left[\phi_1(s,t) - \phi_2(s,t) \right]$$

Defining the mean velocity of the main stream across the jet as

$$U(s,t) = \frac{u_1(s,t) + u_2(s,t)}{2}$$

the velocity difference can be expressed from the above equation together with Eq. (5) as

$$u_1(s,t) - u_2(s,t) = \frac{J(s,t)}{\rho_o U(s,t)\ R(s,t)} - \frac{1}{U(s,t)} \frac{\partial}{\partial t} \left[\phi_1(s,t) - \phi_2(s,t) \right] \tag{7}$$

In contrast to the steady case one now has an additional term in the form of the time derivative of the velocity potential difference.

For the limiting case of an infinitely thin, high-speed jet whose jet thickness $\delta \to 0$ tends to zero it is possible to relate the jet vortex strength to the velocity difference across the jet, hence

$$\gamma_J(s,t) = u_1(s,t) - u_2(s,t) \tag{8}$$

For a rigorous proof compare Erickson (1962). In this limit $V(s,t)$ must become infinite for finite momentum flux although the flow is still considered incompressible. Eqs. (7) and (8) then become

$$\gamma_J(s,t) = \frac{J}{\rho_o U(s,t)\, R(s,t)} - \frac{1}{U(s,t)} \frac{\partial}{\partial t} \left[\phi_1(s,t) - \phi_2(s,t) \right] \tag{9}$$

To complete the problem formulation it is necessary to enforce the flow tangency (kinematic) boundary condition on the airfoil and jet. The linearized approximation of this condition states that the downwash is given by the linearized convective derivative of the airfoil and jet ordinate (see e.g. Karamcheti 1966), i.e.

$$w(x,t) = \frac{\partial Y(x,t)}{\partial t} + U_o \frac{\partial Y(x,t)}{\partial x} \equiv \frac{DY(x,t)}{Dt} \qquad 0<x<\infty \tag{10}$$

Where the airfoil extends from $0<x<\infty$.

Linearizing also the jet curvature

$$\frac{1}{R(s,t)} = -\left[1 + \left(\frac{\partial Y(x,t)}{\partial x}\right)^2\right] \frac{\partial^2 Y(x,t)}{\partial x^2} \simeq -\frac{\partial^2 Y(x,t)}{\partial x^2} \tag{11}$$

one obtains for Eqs. (5) and (9)

$$\Delta p(x,t) = \frac{1}{2} \rho_o U_o^2 c\, c_J \frac{\partial^2 Y(x,t)}{\partial x^2} \qquad c<x<\infty \tag{12}$$

and

$$\gamma_J(x,t) = -\frac{1}{2} U_o c\, c_J \frac{\partial^2 Y(x,t)}{\partial x^2} - \frac{1}{U_o} \frac{\partial \Delta\phi(x,t)}{\partial t} \qquad c<x<\infty \tag{13}$$

Where s has been replaced by x due to the linerization and the jet momentum coefficient

$$C_J = \frac{J}{\frac{1}{2} \rho_o U_o^2 c} \tag{14}$$

has been introduced.

Using

$$2u(x,o,t) = \gamma(x,t) = \frac{\partial \Delta\phi(x,t)}{\partial x} \qquad o<x<\infty \tag{15}$$

the potential difference can be expressed from Eq. (13) as

$$\frac{D\Delta\phi(x,t)}{Dt} = \frac{\partial \Delta\phi(x,t)}{\partial t} + U_o \frac{\partial \Delta\phi(x,t)}{\partial x} = -\frac{1}{2} U_o^2 c\, c_J \frac{\partial^2 Y(x,t)}{\partial x^2} \qquad c<x<\infty$$

and differentiating this equation with respect to x gives

$$\frac{D\gamma_J(x,t)}{Dt} = \frac{\partial \gamma_J(x,t)}{\partial t} + U_o \frac{\partial \gamma_J(x,t)}{\partial x} = -\frac{1}{2} U_o^2 c\, c_J \frac{\partial^3 Y(x,t)}{\partial x^3} \qquad c<x<\infty \tag{16}$$

Representing now both the airfoil and jet by vortex distributions the downwash due to these vortex distributions is found from the Biot-Savart law giving the well known equation

$$w(x,t) = -\frac{1}{2\pi}\int_0^\infty \frac{\gamma(\xi,t)\,d\xi}{\xi - x} \qquad o<x<\infty \tag{17}$$

If one writes

$$w(x,t) = \begin{cases} w_W(x,t) & o\le x\le c \\ w_J(x,t) & c<x<\infty \end{cases}$$

and

$$\gamma(x,t) = \begin{cases} \gamma_W(x,t) & o\le x\le c \\ \gamma_J(x,t) & c<x<\infty \end{cases}$$

then Eq. (17) can be inverted using one of several techniques (see Heaslet and Lomax 1954, Carleman 1922 or Cheng and Rott 1954) leading to the following equation on the semi-infinite interval $x>c$

$$w_J(x,t) + \frac{1}{2\pi}\left(\frac{x-c}{x}\right)^{1/2}\int_c^\infty \left(\frac{\xi}{\xi-c}\right)^{1/2}\frac{\gamma_J(x,t)}{\xi-x}\,d\xi = -\frac{1}{\pi}\left(\frac{x-c}{x}\right)^{1/2}\int_0^c \left(\frac{\eta}{c-\eta}\right)^{1/2}\frac{w_W(x,t)}{\eta-x}\,d\eta \tag{18}$$

$w_W(x,t)$ is known from the flow tangency on the airfoil Eq. (10) for known airfoil motion. Along the jet this condition is

$$\left(\frac{\partial}{\partial t} + U_o\frac{\partial}{\partial x}\right) h_J = w_J \tag{19}$$

where $Y(x,t) = h_J(x,t)$ is the jet deflection below the x-axis. In addition, one has the dynamic jet condition Eq. (16)

$$\left(\frac{\partial}{\partial t} + U_o\frac{\partial}{\partial x}\right)\gamma_J = -2\mu c\, U_o^{\,2}\,\frac{\partial^3 h_J}{\partial x^3} \tag{20}$$

where $\mu = \dfrac{J}{2\rho_o U_o^{\,2} c} = \dfrac{1}{4}\, c_J$ (21)

Eqs. (18), (19) and (20) are the basic starting equations for the solution of the unsteady jet flap problem within the linearized thin-jet approximation. They are three equations for the three unknowns $\gamma_J(x,t)$, $w_J(x,t)$ and $h_J(x,t)$, but with prescribed wing motion $w_W(x,t)$ and prescribed variation of $\left(\frac{\partial h_J}{\partial x}\right)(c,t)$, the jet slope at the airfoil trailing-edge. For a more detailed derivation and discussion of this problem formulation compare Spence 1961 and Erickson 1962.

2.2 Spence's Oscillatory Flow Solution

Assuming purely harmonic time dependence Spence (1965) has given an approximate solution of the above system of equations. Three cases are of interest, namely a) the stationary airfoil with oscillating jet flap, b) the periodically plunging airfoil c) the periodically pitching airfoil.

For case a) the airfoil remains fixed at zero angle of attack, hence

$$h_W(x,t) = 0 = w_W(x,t) \tag{22}$$

In cases b) and c) the airfoil moves but the jet emerges at all times tangentially at the trailing-edge.

Replacing $h_J(x,t)$ and $\delta_J(x,t)$ by $e^{i\omega U_o t/c}\, h_J(x)$ and $e^{i\omega U_o t/c}\, \gamma_J(x)$ Eqs. (18) and (19) combine into

$$(i\omega + c\frac{d}{dx})\ h_J(x) = -\frac{c}{2\pi U_o}\left(\frac{x-c}{x}\right)^{1/2}\int_c^\infty \left(\frac{\xi}{\xi-c}\right)^{1/2}\frac{\gamma_J(\xi)}{\xi-x}\,d\xi \tag{23}$$

Eq. (20 becomes

$$(i\omega + c\frac{d}{dx})\ \gamma_J(x) = -\ 2\mu c^2\ U_o\ \frac{d^3 h_J}{dx^3} \tag{24}$$

and the boundary condition is

$$h_J'(c) = \tau = \text{Const}, \quad h_J(c) = 0$$

Spence proposed a "weak-jet" approximation to this pair of equations by assuming the jet strength parameter μ to be small with respect to unity or, equivalently, C_J to be small with respect to 4. "Stretching" the trailing-edge region by the coordinate transformation

$$\bar{x} = (x-c)/\mu c \tag{25}$$

he derived an approximation to Eqs. (23) and (24) which is dependent only on the single parameter

$$\nu = \mu\omega \tag{26}$$

The resulting singular third-order integro-differential equation then becomes mathematically tractable. Spence found solutions to exist only for values of $\nu \leq 2$ and computed jet shapes and lift forces for both the oscillatory jet case a) and the plunging case b) for a range of values of ν. Erickson (1970) later extended this approach to the harmonically pitching airfoil, case c), and presented lift and pitching moment results.

According to Erickson it is important to note the "boundary layer" character of this solution which was obtained by the stretching transformation Eq. (25) and then setting μ equal to zero whenever it appeared explicitly in the transformed equations. The neglect of the finite μ terms, together with the transformation, emphasizes the jet just downstream of the trailing-edge and restricts the validity of the solution to high frequencies. This follows from the assumption that the characteristic length c and the characteristic

wavelength of the oscillation, given by $2\pi c/_{\omega}$, must both be of the same order. This implies that ω be of order 2π or greater.

An interesting finding is the breakdown of the solution for values of $\nu > 2$. Although no completely satisfactory explanation seems obvious, Spence hypothesizes the existence of a critical "Strouhal number" indicating a wake instability.

2.3 Potter's Approach

Potter (1972) approached the problem as an initial value problem in time using point vortex distributions and thus reducing Eq. (17) to finite difference form. The jet is initially specified as a straight horizontal line with zero vorticity, after which time the jet exit angle is either instantaneously deflected or continuously oscillated. By accounting for all the changes in bound airfoil vorticity and by assuming that the shed vortices are propagated downstream with the free-stream velocity, conservation of circulation is maintained for each time step and the jet shape is determined by computing the downwash and the resultant velocities at each jet vortex point. As is common with point vortex methods, erratic vortex motions were found to build up with increasing time steps. Although no completely satisfactory solution to this problem was found, the adoption of an averaging scheme over several neighboring vortices gave seemingly satisfactory results for jet momentum coefficients smaller than 0.1. Above this value the procedure was unstable.

3. Unsteady Jet Flap Experiments

In the late 1960's several investigators started to conduct wind tunnel tests on oscillating jet-flapped airfoils in an effort to determine their unsteady aerodynamic characteristics.

3.1 The Work of Simmons and Platzer

Simmons and Platzer (1970) studied a two-dimensional NACA 0012 airfoil of 12-inch chord and 18-inch span. The aft 15% of the chord was removed and replaced across the full span by a circular steel tube with 0.5-in. o.d. as shown in Fig. 2. There was no gap between the tube and the airfoil and the tube was free to rotate in bearings at each end. It served as a plenum for the jet flap which was formed by a row of 0.029-in. diameter holes spaced 0.25 inches apart along the trailing edge of the tube across the full span. Fig. 3 shows the test set-up. The airfoil was clamped between two rectangular end plates extending from the tunnel roof to the floor and extending 0.6 chord lengths upstream and 2.6 chord lengths downstream of the airfoil. The tests were performed in the Lockheed-Georgia Low Speed Wind Tunnel which has a test section 30 in. high, 43 in. wide and 58 in. long. The jet flap's oscillation was accomplished by extending the plenum tube through a bearing in one of the end plates and coupling it to the shaft of an electrohydraulic servo-motor fastened to the rear wall of the tunnel. The jet deflection angle could then be varied, at frequencies up to 30 cps, by rotational oscillation of the plenum tube. The airfoil instrumentation consisted of 21 pressure tappings that were located on both the upper and lower surface along the chord at mid-span. These tappings were connected through a scanning valve to a single pressure transducer located outside the tunnel. Thus, the expense and calibration

of a large number of transducers located directly on the airfoil surface was avoided. Instead, the frequency dependent transfer function of the tube-scanning valve system had to be determined to reduce transducer outputs to actual pressures on the airfoil surface. This technique was first pioneered by H. Bergh (1964) of the National Aerospace Laboratory.

The tests were performed with the model set at zero angle of attack and with the jet flap oscillating about the airfoil chord line at 13 degree amplitude. The tunnel speeds were 103 and 51 fps giving jet momentum coefficients of 0.14 and 0.58. Typical differential pressure distributions are shown in Figs. 4, 5 and 6 for three frequencies of oscillations, 1, 10 and 22 cps. These pressure distributions were then integrated to give the coefficients and their phase relative to the plenum tube position which are presented in Fig. 7.

3.2 The Work of Trenka

Trenka (1970) investigated a two-dimensional NACA 0015 airfoil having a 12-inch span and a 6-inch chord with a 20% flap over the entire span. The jet exhausted over the upper flap surface from a span-wise slot at 80% chord. The airfoil was bolted to a main support tube which was supported in bearings located at 38% chord. By means of electromagnetic shakers and suitable shaker arms the wing and flap could be excited so that jet flap oscillations as well as wing pitching oscillations could be generated. The wing and support tube were attached to a three-component strain-gage balance permitting the measurement of the loads perpendicular and parallel to the wing chord plane and the pitching moments about the wing pitch axis. The tests were conducted in the subsonic leg of the Cornell Aero Lab High-Speed Wind Tunnel

having a test section 17 inches wide, 32 inches high and 32 inches long. The dynamic tests were performed with and without a tunnel velocity in order to provide information about the balance inertia loadings at zero wind speed. Both, wing and flap were set at zero angle and the tests were run with and without jet blowing. Also, a number of pressure transducers were mounted on the upper and lower airfoil surface to give static and oscillatory pressure information. Results are shown in Figs. 8 and 9.

3.3 The Work of Takeuchi

A third series of tests was completed at about the same time by Takeuchi (1970). Again, a dynamic balance was used to determine the oscillatory forces and moments rather than direct pressure measurements. The semi-span wing model had a rectangular planform with a 7.5-inch chord and a 24-inch semi-span. The profile approximated a NACA 63_2A015 airfoil. A plain trailing edge flap of 0.65-inch chord was attached to the wing over the full span for the purpose of varying the jet angle which emanated from blowing slots at the top and bottom of the wing trailing edge. An eccentric arm of adjustable length driven by an electric motor was used to generate flap oscillations of variable amplitude. The wing was mounted on a strain gage balance which provided a measure of the lift at any instant of time. The tests were performed in the 3 ft x 3 ft subsonic tunnel of the Pennsylvania State University. The tunnel speed was kept constant at 56.5 ft/sec, permitting jet coefficients up to 0.5. Using galse walls various aspect ratios could be simulated, ranging from 2.1, 4.1, 6.4 to infinity. Some of the results are shown in Figs. 10 and 11.

3.4 The Work of Kretz

Kretz (1973) completed another series of tests closely paralleling the work of Simmons and Platzer (1970). The NACA 0012 airfoil tested had a span of 1000 mm and a chord of 400 mm. The last 20% were replaced by a flexible flap to achieve various jet deflection angles. The measuring technique was based on the previously described NLR-technique (Bergh 1964) requiring the tube transfer functions. The tests were conducted in the ONERA S2L tunnel (no test section dimensions were given) at a wind speed of 40 m/sec, permitting tests at jet momentum coefficients of 0.25, 0.5 and 1.0. The results are shown in Fig..12.

3.5 The Work of Simmons

Very recently, Simmons (1974) completed another series of tests on a NACA 0012 airfoil which had a chord of 150.9 mm and a span of 461 mm. This experiment was performed in the Low Speed Wind Tunnel of the University of New South Wales, Australia, which has essentially a 0.461 mm x 0.461 mm square test section except for corner fillets. Again, the measuring technique was the same as the one previously used by Simmons and Platzer (1970). The airfoil could be excited into sinusoidal pitch or plunge oscillation by a precision Scotch yoke mechanism acting through proper linkages, while the jet flap was held stationary with respect to the airfoil. The jet momentum coefficient could be varied up to 1.76 running at tunnel speeds of 12.3 and 24.6 m/sec corresponding to Reynolds numbers of 1.29×10^5 and 2.58×10^5. Some of the results obtained in these tests are shown in Figs. 13 and 14.

4. Comparison and Evaluation of Tests and Theories

4.1 Fixed Airfoil with Oscillating Jet Flap

The results of Spence, Simmons and Platzer, Takeuchi, Potter and Kretz are compared in Figs. 15 and 16. It is immediately apparent that there is relatively good agreement between Spence's theory and Takeuchi's experiment on the one hand, and between Potter's theory and the experiments of Simmons and Platzer and Kretz on the other hand. The large discrepancy between these two sets of theories and experiments must remain largely unexplained until further experimental and theoretical work is accomplished. At this time only the following observations can be offered:

a) As previously explained Spence's theory appears to be valid only for reduced frequencies $\omega > 2\pi$ and a comparison of this theory in the lower frequency range may therefore be misleading.

b) The deviations between the experiments of Simmons and Platzer and Kretz may be caused by the different trailing-edge and jet configurations. Simmons and Platzer used a blunt trailing-edge and many discrete holes rather than a continuous slot for jet blowing, whereas Kretz had a sharp trailing-edge and a continuous jet sheet.

c) The major unresolved discrepancy remains between the dynamic balance measurements of Takeuchi and the pressure measurements of Simmons and Platzer and Kretz which produced quite opposite trends for both lift amplitude and phase angle with frequency.

4.2 Periodically Pitching and Plunging Jet Flapped Airfoil

Simmons (1975) compared his recent results (section 3.5) with Spence's predictions and Trenka's experiments. Again, the theory disagrees with the experimental trends over the reduced frequency range ($\omega<2\pi$) tested but this may be explainable by the inapplicability of the theory in this range. However, the irreducibility of Spence's results for lift and pitching moment to the well-known jet-off results as the jet momentum coefficient approaches zero is particularly disturbing and requires further investigation. Trenka's experimental results, on the other hand, are too limited to allow meaningful comparisons.

5. Applications

The potential of the jet flap as a fast acting lift control device seems to have been first recognized by W. R. Sears in the late fifties (according to a remark by Spence in Ref. 19). Since then a number of applications have been made or proposed which we will briefly discuss.

5.1 Air Stream Oscillator

The need for practical and efficient airstream oscillators in wind tunnel dynamic response studies is well recognized. Several devices have been investigated in recent years to find alternatives to the presently used oscillating vane arrangements (such as the one used in the Langley Transonic Dynamics Tunnel, Ref. 1) Jacobs and Platzer (1969) proposed mechanically or fluidically oscillated jet flaps for airstream oscillation. A typical configuration is shown in Fig. 17 which was tested by Simmons and Platzer (1970). Further work along these lines was recently pursued by Viets (1975) and Ham (1975). Viets (1974) developed a new fluidic oscillator which appears to be well suited for high frequency gust generation. Ham (1975) adopted the circulation control principle rather than the jet flap principle. His set-up is similar to the one used by Simmons and Platzer but has the advantage of significantly lower required blowing rates. Test data on the performance of these devices can be found in Refs. 17 and 18.

5.2 Gust Response and Vibration Controller

In recent years extensive studies have been conducted on active load alleviation, mode stabilization and vibration control of both aircraft wings and helicopter rotor blades using conventional control surfaces and spoilers as control devices (see e.g. Refs. 13,20). Helicopter blades can experience a

particularly complex non-uniform flow field due to the interception of vortices produced by preceding blades. The forces produced by these flow non-uniformities may excite higher modes of harmonic vibration and high frequency stresses leading to premature blade failure. Closed-looped control techniques utilizing pressure, lift or strain sensing on the blade section therefore appear as an attractive method of vibration and load control. The application of the jet flap to this problem has been studied extensively by Giravions Dorand (Refs. 11, 13) and to a lesser extent by Honeywell Inc. (Ref. 2). Giravions Dorand conducted a series of wind tunnel tests on a jet flap rotor to reduce the vibrations and stresses by multi-cyclic jet flap control. At a tip speed ratio of 0.4 reductions up to 50% were attained. Concurrent theoretical studies showed that further reductions up to 80% are possible. Honeywell investigated the Variable Deflection Thruster (VDT) concept (Fig. 18). The VDT allows control of both the angle and magnitude of a jet by mixing of two separate jets. The two jets are supplied from two separate plenum chambers and meet on the surface of the blunt trailing-edge at a position determined by their momentum difference. A different jet actuation scheme was developed by Simmons and Platzer (1970). The effectiveness of this device to alleviate the gust response of an airfoil having the pitch degree of freedom only was demonstrated by Platzer, Deal and Johnson (1975).

REFERENCES

1. Abbott, F. T., Jr., "Brief Description of the Characteristics of the Langley Transonic Dynamics Tunnel Airstream Oscillator," Paper 6, Sept. 24-25, 1968, Meeting on Aircraft Response to Turbulence, NASA Langley Research Center.

2. Bailey, R. G. and J. M. Hammer, "Helicopter Application Studies of the Variable Deflection Thruster Jet Flap", Honeywell Document No. 12153-FR1(R), November 1970.

3. Bergh, H., "A New Method for Measuring the Pressure Distribution on Harmonically Oscillating Wings," Rept. MP 224, 1964, National Aerospace Laboratory, NLR, Amsterdam.

4. Carleman, T. (1922) "Sur la resolution de certaines equations integrales" Arkiv For Matematik, Astronomi Och Fysik, Band 16, No. 26, May 1922, pp. 1-19.

4. Cheng. H. K. and Rott, N. (1954) "Generalization of the Inversion Formula of Thin Airfoil Theory" Journal of Rational Mechanics and Anaylsis, Vol. 3, No. 3, May 1954, pp. 357-382.

6. J. C. Erickson Jr., "A Theory for Unsteady Motions of Jet-Flapped Thin Airfoils", Ph.D. thesis, Cornell University 1962.

7. Ham, N. D., Bauer, P. H. and T. L. Lawrence, "Wind Tunnel Generation of Sinusoidal Lateral and Longitudinal Gusts by Circulation Control of Twin Parallel Airfoils", NASA CR 137547, August 1974.

8. Heaslet, M. A. and Lomax, H. (1954) "Supersonic and Transonic Small Perturbation Theory" Article D of "General Theory of High Speed Aerodynamics," Volume VI of High Speed Aerodynamics and Jet Propulsion, Princeton University Press, 1954.

9. W. F. Jacobs and M. F. Platzer, "Airfoil Including Fluidically Controlled Jet Flap", U. S. Patent 3,669,386, June 13, 1972.

10. Karamcheti, K., "Principles of Ideal Fluid Aerodynamics", Wiley 1966.

11. M. Kretz, "Commande asservie des forces aerodynamiques instationnaires", Rep. DE 07-44E5, Giravions Dorand, December 1973.

12. M. L. Lopez, C. C. Shen and N. F. Wasson, "A Theoretical Method for Calculating the Aerodynamic Characteristics of Arbitrary Jet-Flapped Wings", Report No. MDC J5519, Vol. I and II, Douglas Aircraft Company, May 1973.

13. J. L. McCloud III and M. Kretz, "Multicyclic Jet-Flap Control for Alleviation of Helicopter Blade Stresses and Fuselage Vibration", Paper No. 23, Specialists' Meeting on Rotorcraft Dynamics, NASA Ames Research Center, February 1974.

14. Platzer, M. F., Deal, L. J. and Johnson, W. S., "Experimental Investigations of Oscillatory Jet Flow Effects", Proceedings of Symposium on Unsteady Aerodynamics sponsored by U. S. Air Force Office of Scientific Research, University of Arizona, Tuscon, Arizona, pp. 393-414, July 1975.

15. Potter, G. E., "A Numerical Solution for an Unsteady Jet-Flapped Airfoil", Thesis, Pennsylvania State University 1972.

16. Simmons, J. M., "Experimental Aerodynamic Derivatives of a Sinusoidally Oscillating Aerofoil with Jet Flap in Two-Dimensional Incompressible Flow", Res. Rep. No. 11/74, Dec. 1974, Dept. Mechanical Engineering, Uni. of Queensland, Brisbane, Old., Australia.

17. Simmons, J. M., "Private Communication, 1975.

18. Simmons, J. M. and Platzer, M. F., "Experimental Investigation of Incompressible Flow Past Airfoils with Oscillating Jet Flaps", J. Aircraft, Vol. 8, No. 8, Aug. 1971, pp. 587-592.

19. D. A. Spence, "The Flow Past a Thin Wing with an Oscillating Jet Flap", Phil. Trans. Soc. of London, Ser. A, 257, No. 1085, pp. 445-477 (1965).

20. Swaim, R. L., "Aircraft Elastic Mode Control," Journal of Aircraft, Feb. 1971.

21. Takeuchi, K., "Two and Three-Dimensional Unsteady Lift Measurement of Jet-Flapped Wings", M.S. Thesis, Pennsylvania State University, June 1970.

22. A. R. Trenka and J. C. Erickson Jr., "The Determination of Unsteady Aerodynamics of a Two-Dimensional Jet Flap Wing", Rep. No. AC-2260-S-1, Cornell Aeronautical Laboratory, April 1970.

23. H. Viets, "Oscillating Jet Nozzles for V/STOL Application", AIAA Paper No. 74-1189, AIAA/SAE 10th Propulsion Conference, San Diego, Oct. 1974.

24. H. Viets, "High Frequency Gust Tunnel", AGARD-paper to be presented at AGARD Conference on Testing Techniques, London, October 1975.

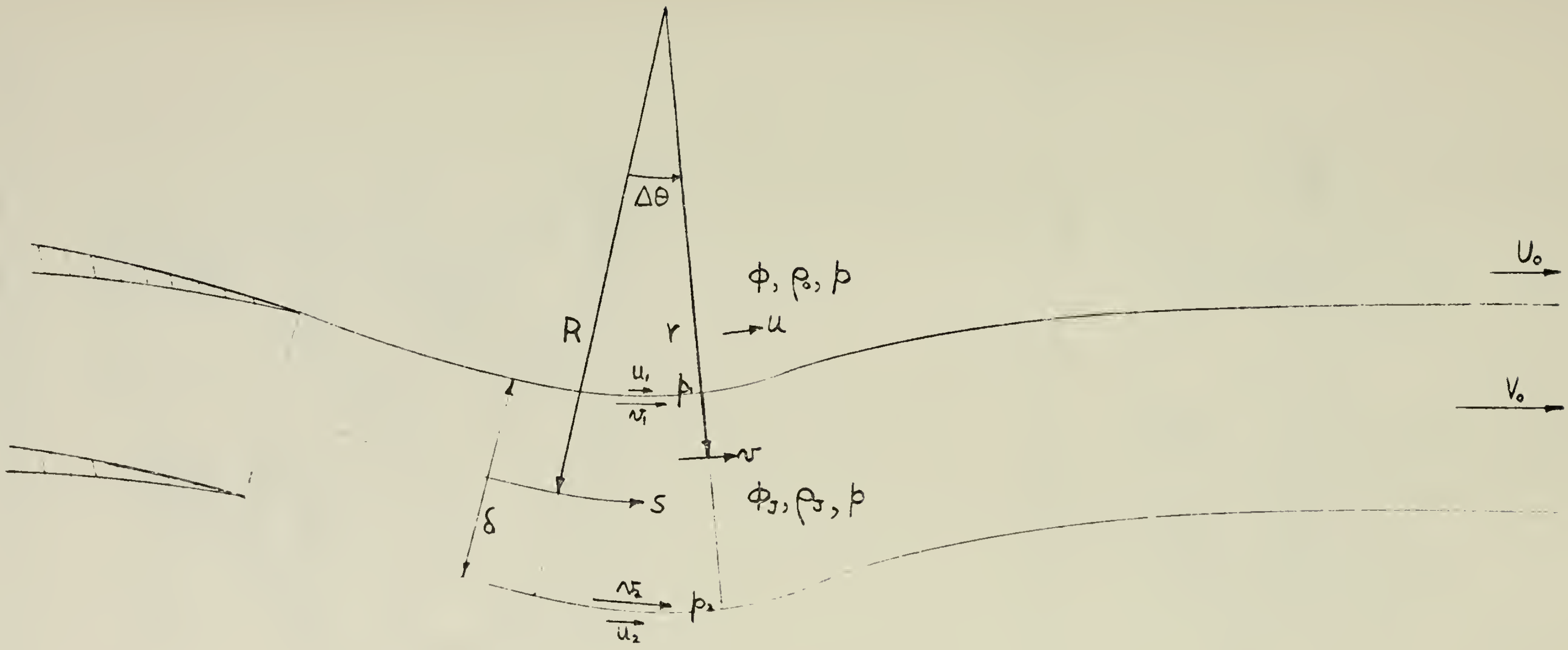


Figure 1 - Flow in an Element of the Jet (Schematic)

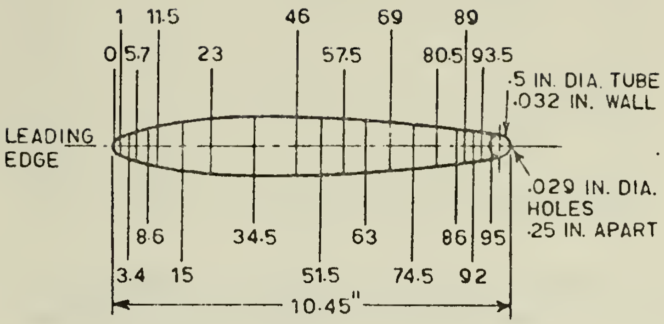


Fig. 2 Airfoil Used by Simmons and Platzer (Ref. 18)

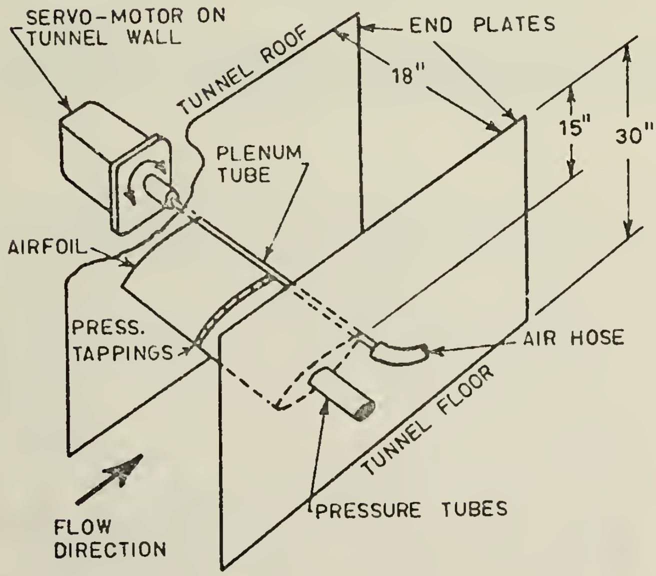


Fig. 3 Jet Flap Model Installation in Wind Tunnel (Ref. 18)

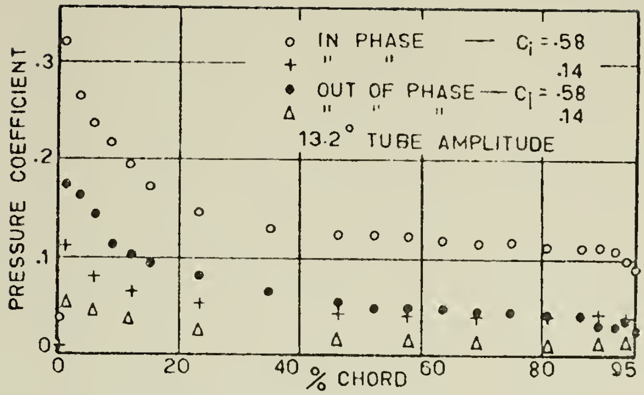


Fig. 4 Differential Pressure Distributions at 1 c.p.s. Obtained by Simmons and Platzer (Ref. 18)

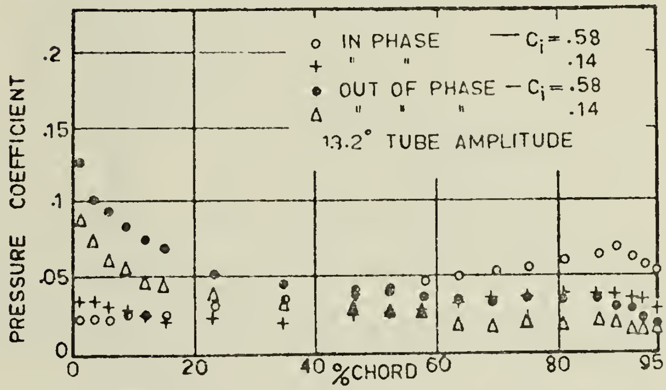


Fig. 5 Differential Pressure Distributions at 10 c.p.s. Obtained by Simmons and Platzer (Ref. 18)

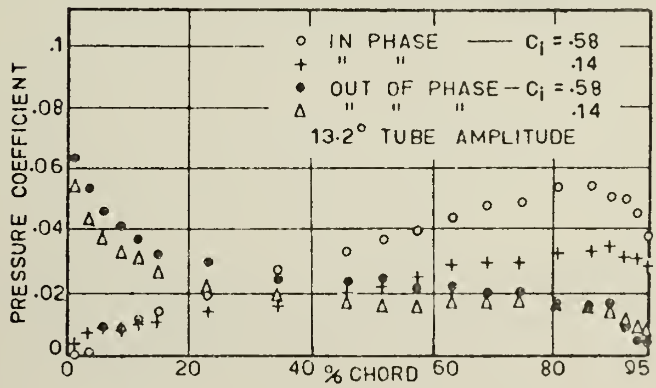


Fig. 6 Differential Pressure Distributions at 22 c.p.s. Obtained by Simmons and Platzer (Ref. 18)

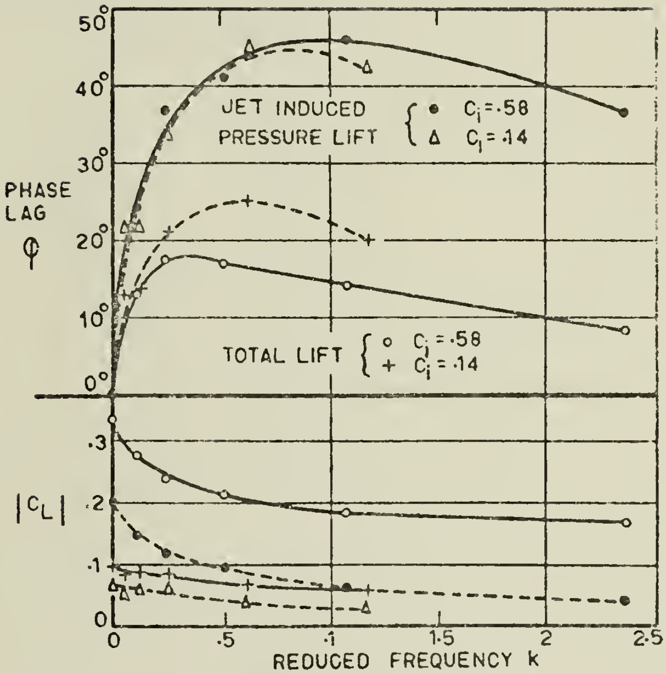


Fig. 7 Measured Lift Amplitude and Phase Angle Obtained by Simmons and Platzer (Ref. 18)

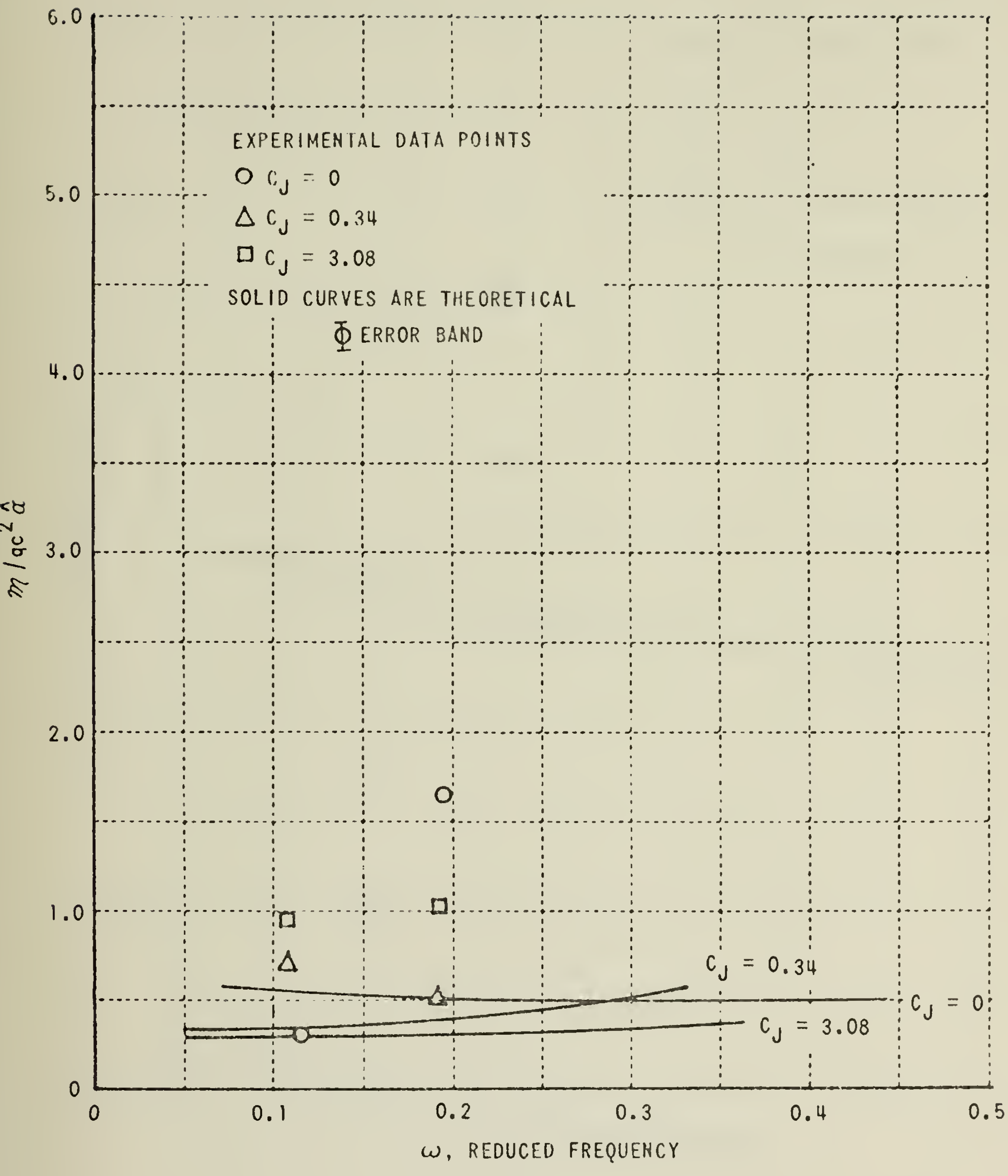


Fig. 8 PLOT OF PITCHING MOMENT COEFFICIENT AMPLITUDE VS REDUCED FREQUENCY
From Trenka and Erickson (Ref. 22)

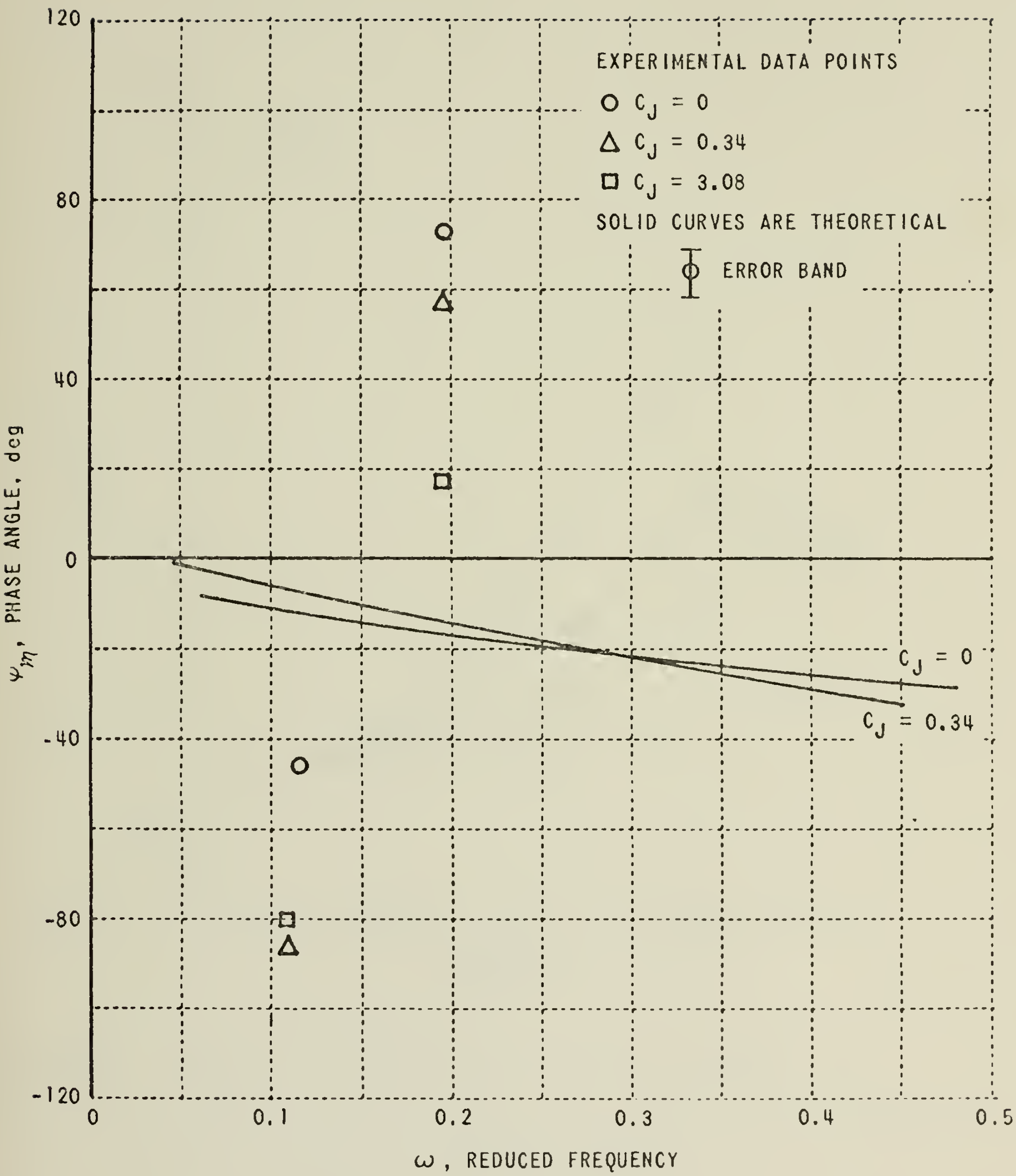


Fig. 9 PLOT OF PITCHING MOMENT PHASE ANGLE VS REDUCED FREQUENCY

From Trenka and Erickson (Ref. 22)

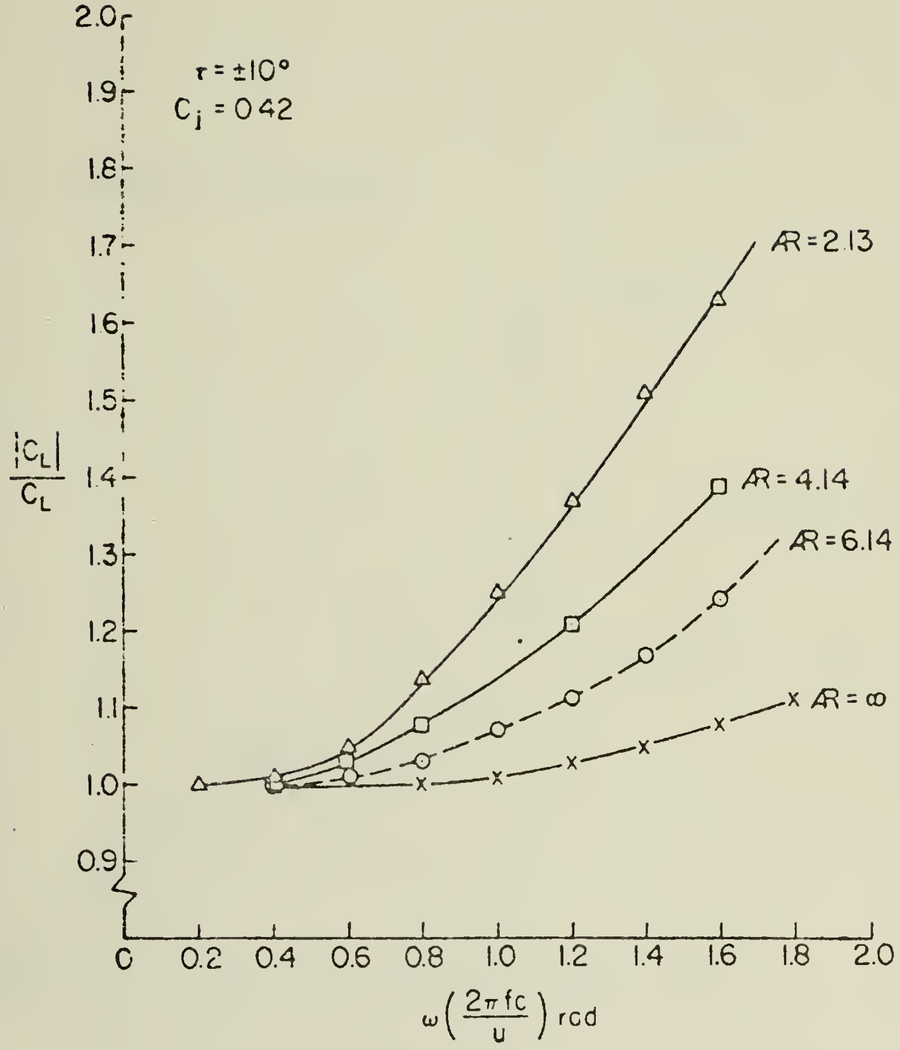


Fig. 10 Variation of $|C_L|/C_L$ with Reduced Frequency for c_j = 0.1 and 0.42, c_j = 0.42 AR = 2.1, 4.1, 6.4 and ∞ From Takeuchi (Ref. 21)

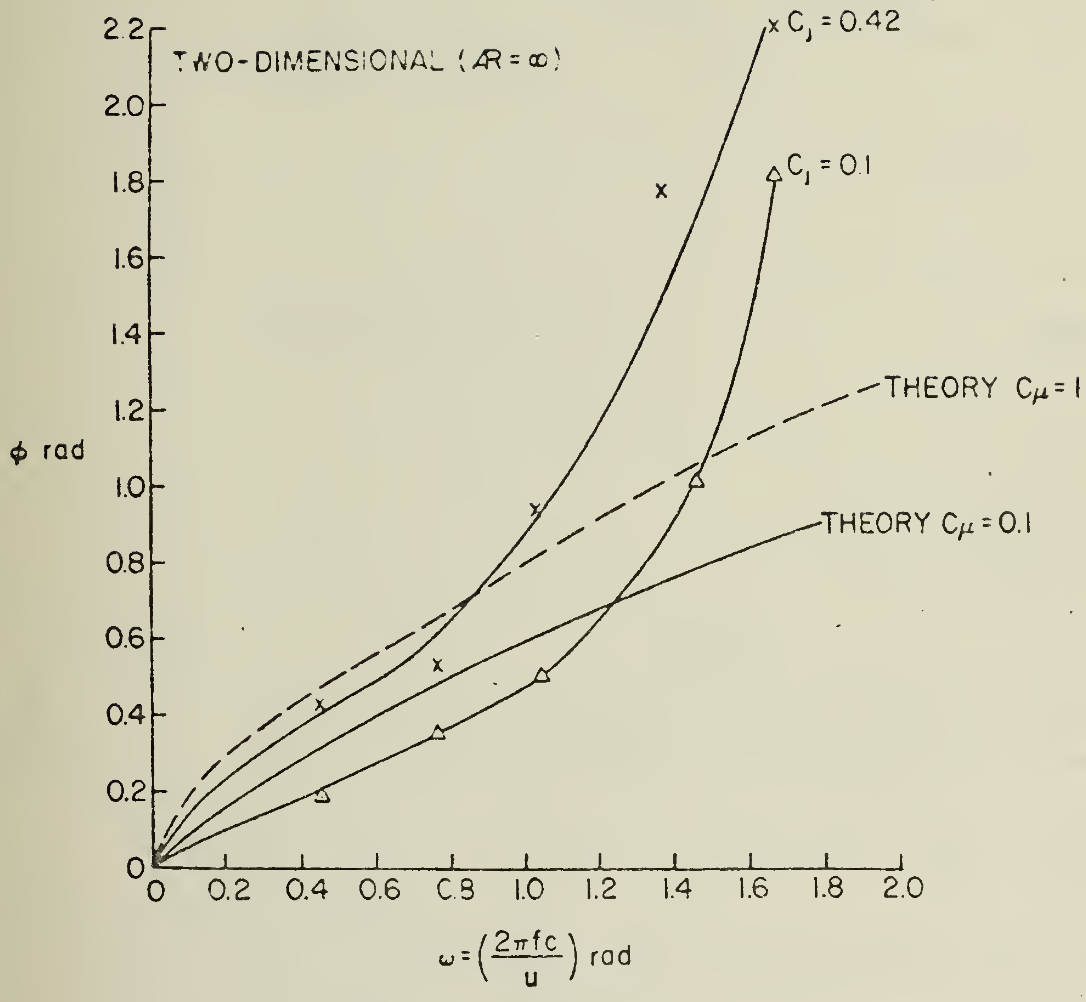


Fig. 11 Variation of Phase Angle with Reduced Frequency at Constant c_j of 0.1 and 0.42 AR = ∞

From Takeuchi (Ref. 21)

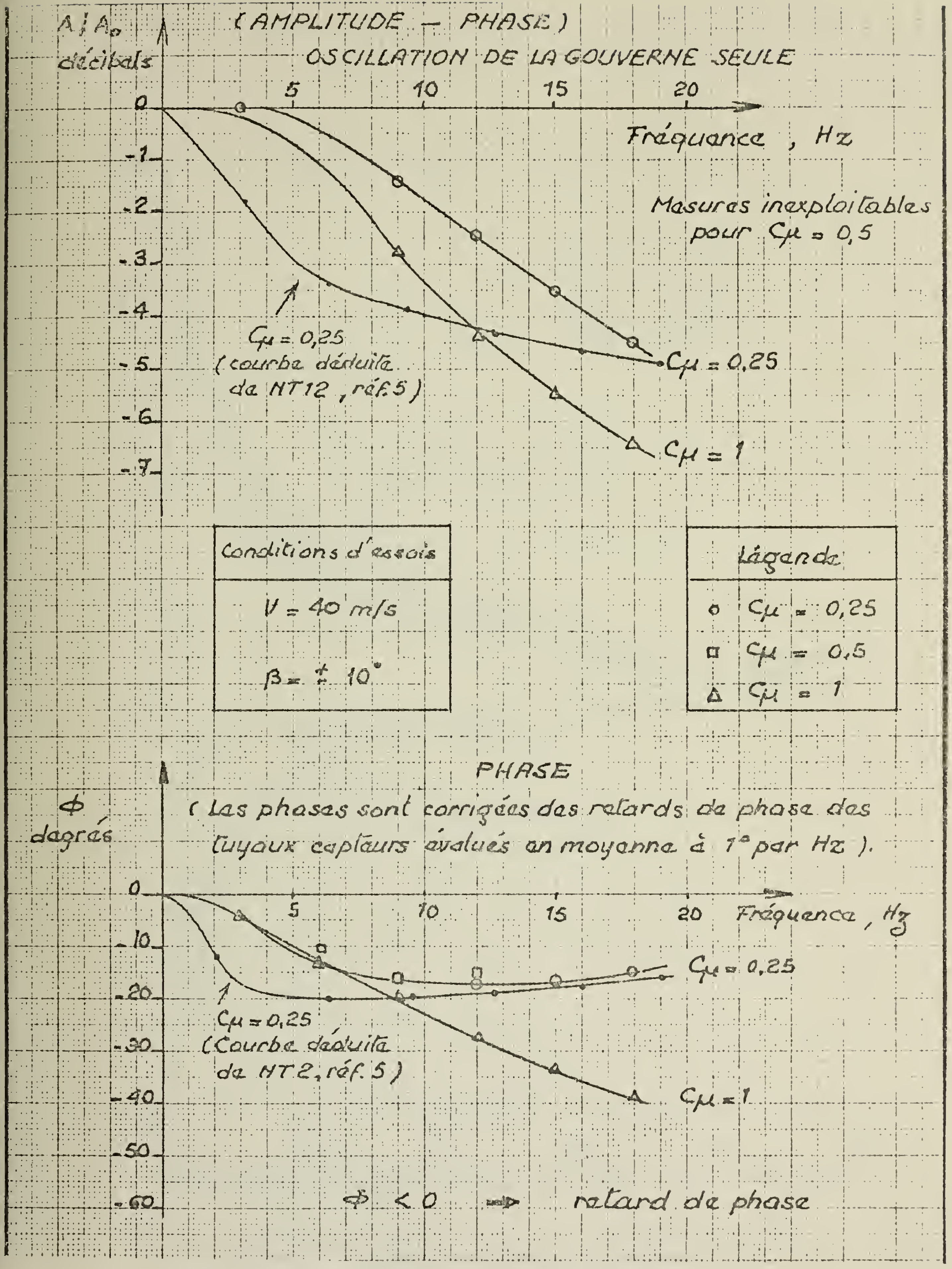


Fig. 12 Measured Lift Amplitude and Phase
Obtained by Kretz (Girarions-Dorand, Ref. 11)

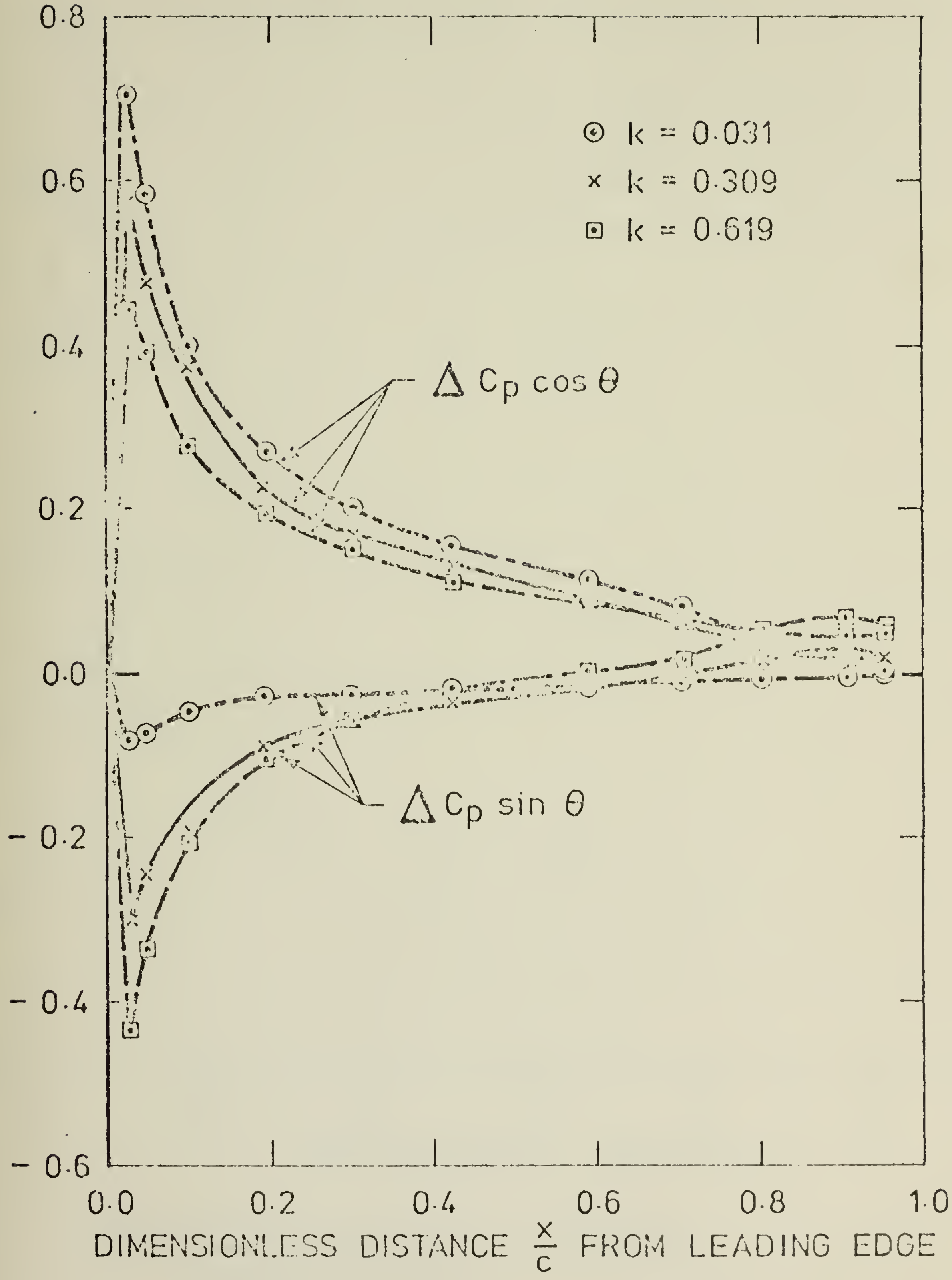


Fig. 13 In-phase and Quadrate Components of Differential Pressure Distribution for Oscillatory Pitching
Obtained by J. M. Simmons (Ref. 16)

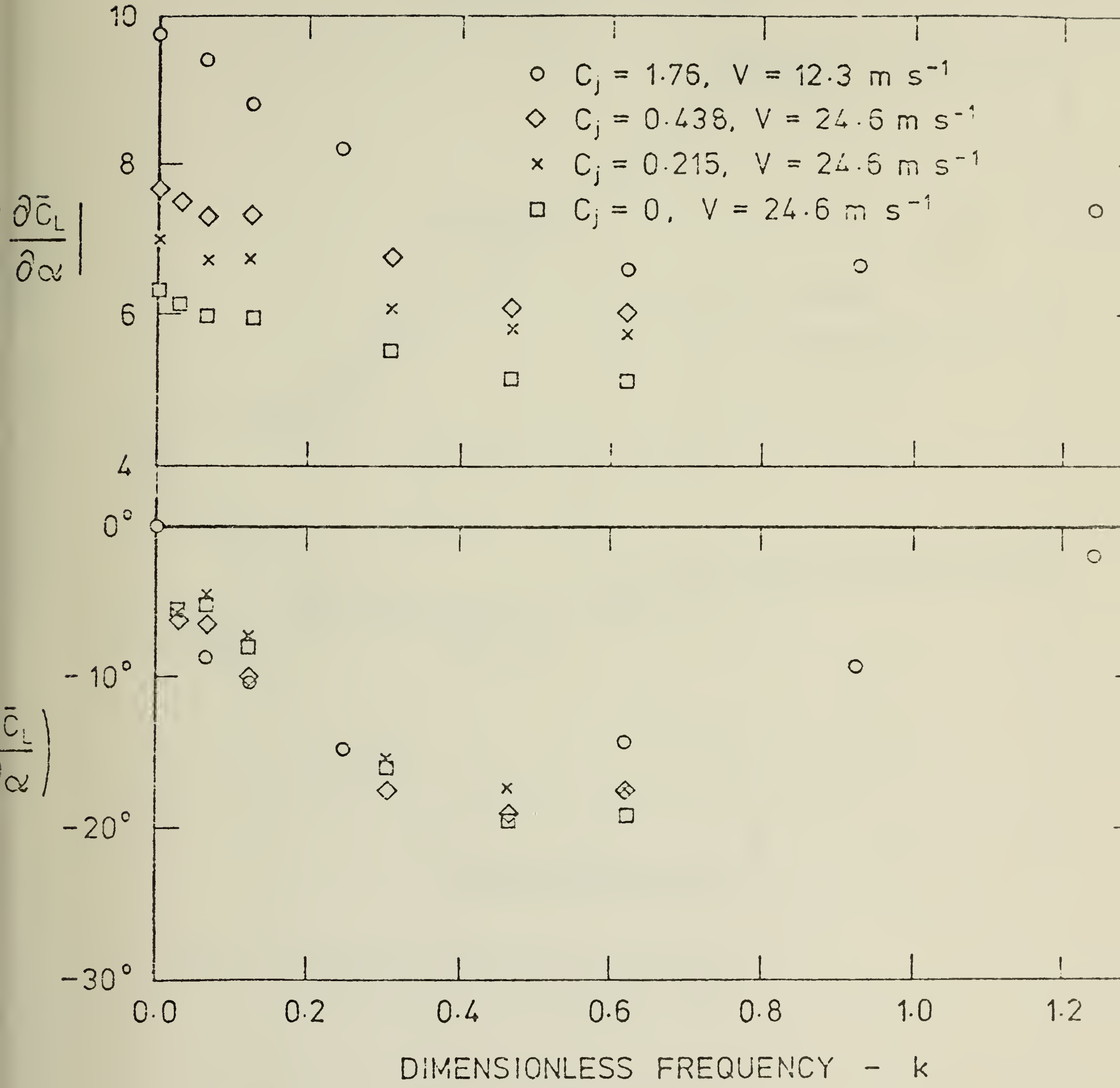


Fig. 14 Measured Lift Response for Oscillatory Pitching of Airfoil
Obtained by J. M. Simmons, to be published in AIAA-Journal

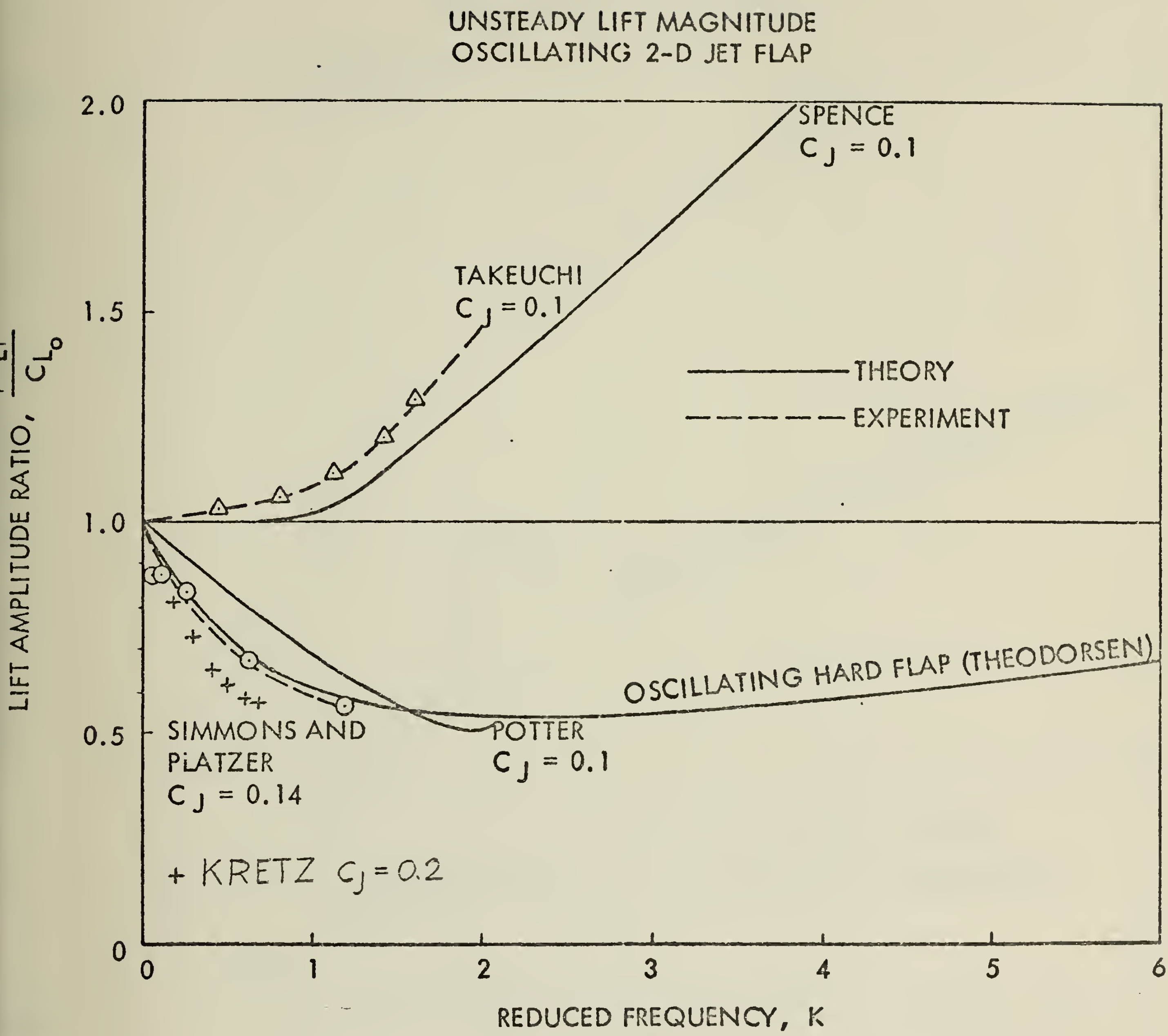


Fig. 15 Comparison of Results for Lift Response of Airfoil with Oscillating Jet Flap

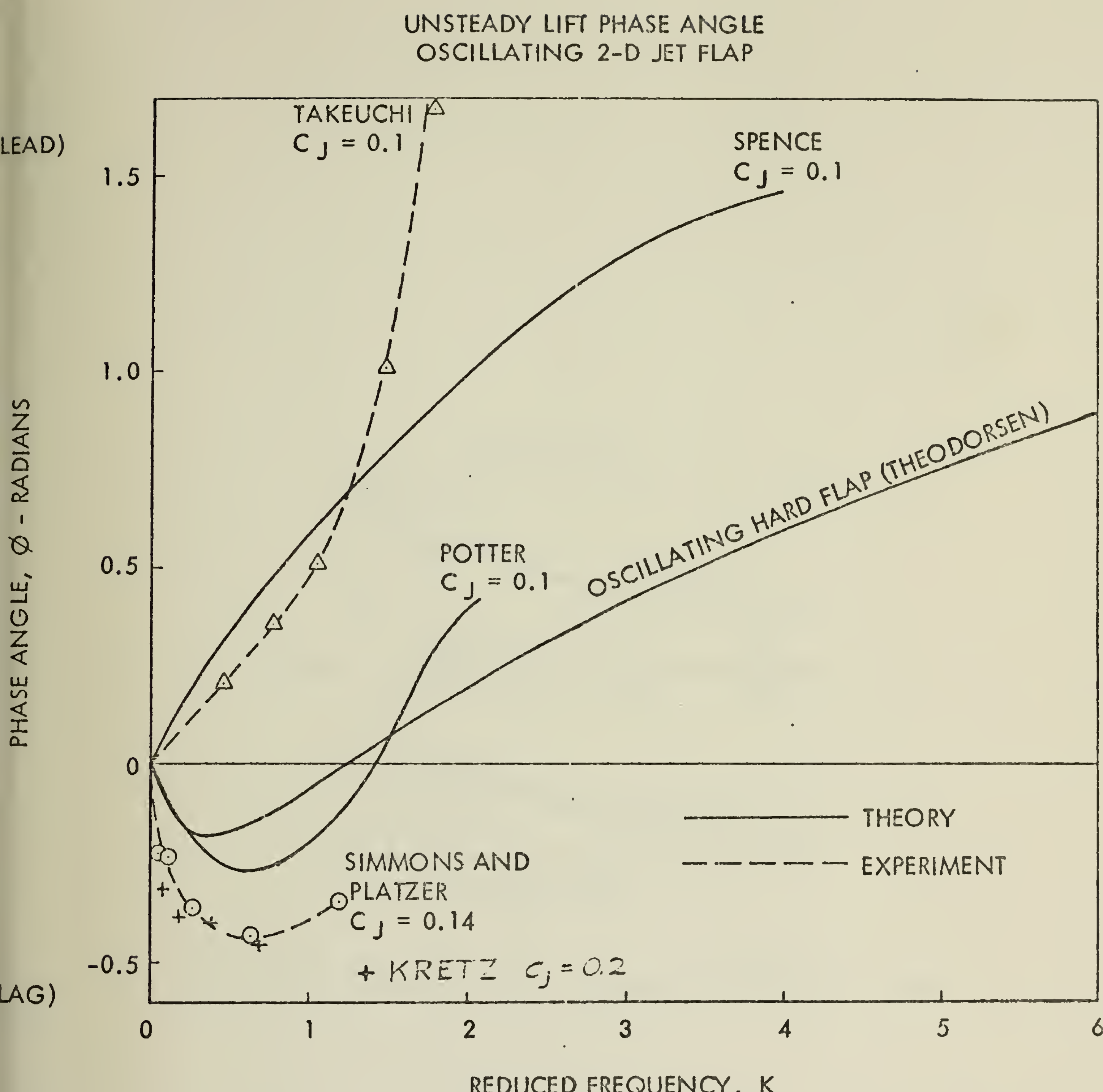


Fig. 16 Comparison of Results for Lift Response of Airfoil with Oscillating Jet Flap

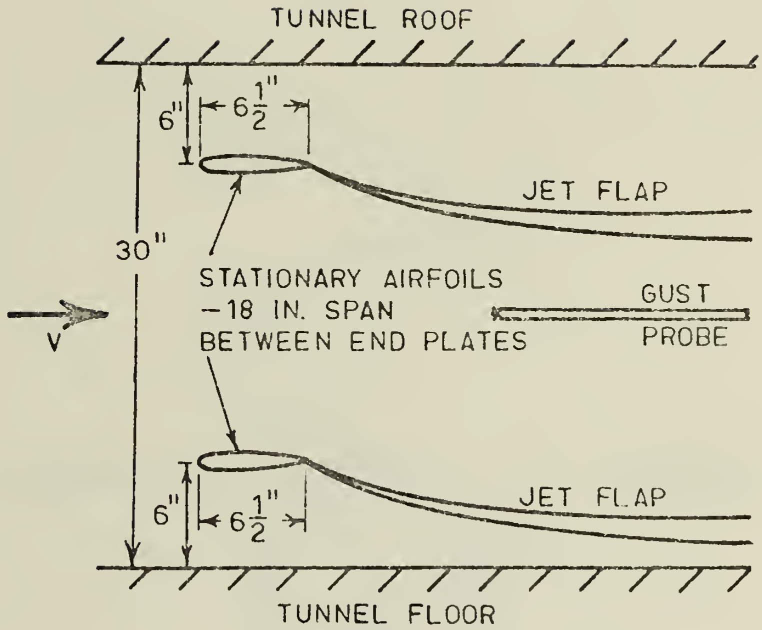
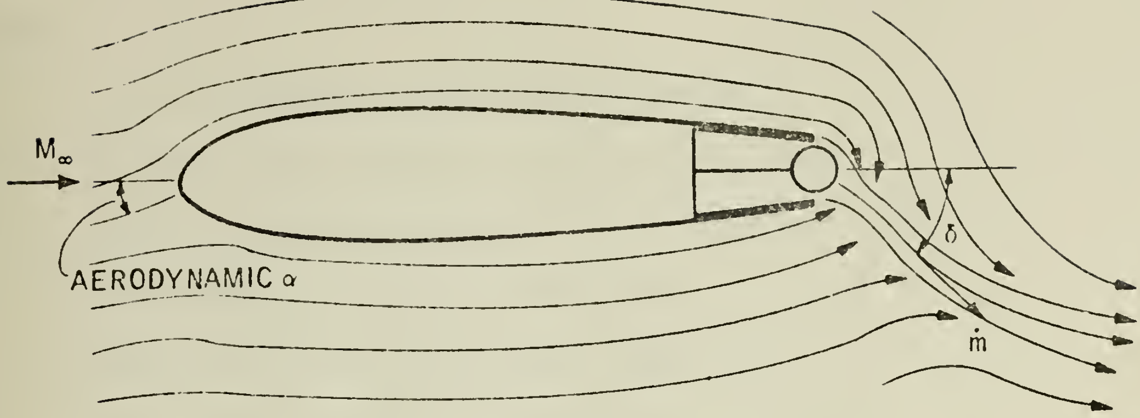
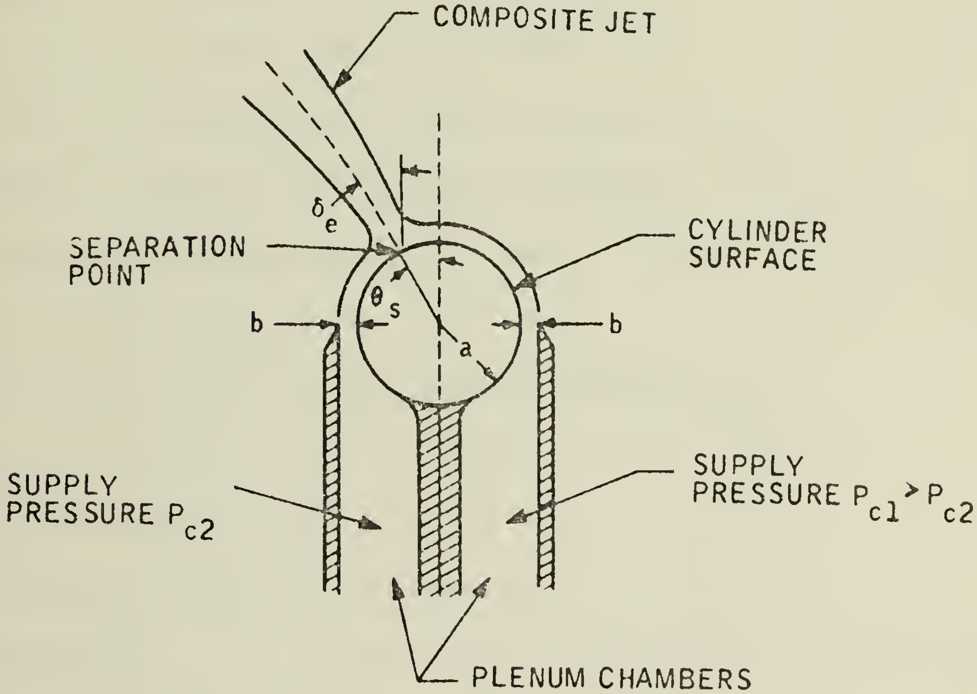


Fig. 17 Gust Generator Used by Simmons and Platzer (Ref. 18)



Airfoil Section with a Variable Deflection Thruster Trailing Edge



Variable Deflection Thruster Schematic Diagram

Fig. 18 From Bailey and Hammer (Ref. 2)

LIST OF FIGURES

DISTRIBUTION LIST

		No. of Copies
1.	Naval Postgraduate School Code 0212 Naval Postgraduate School Monterey, CA 93940	2
2.	Department of Aeronautics Code 57 Naval Postgraduate School Monterey, CA 93940 Prof. R. W. Bell, Chairman Prof. M. F. Platzer	 1 10
3.	Defense Documentation Center Cameron Station Alexandria, VA 22314	2
4.	Dean of Research Code 023 Naval Postgraduate School Monterey, CA 93940	1
5.	Mr. Ray Siewert Code AIR-320 Naval Air Systems Command Washington, DC 20360	1
6.	Mr. John L. McCloud III Research Engineer Mail Stop N247-1 NASA Ames Research Center Moffett Field, CA 94035	1
7.	Dr. John M. Simmons Senior Lecturer Dept. of Mechanical Engineering University of Queensland Brisbane, Australia 4067	1

NPS